FORMATION OF GROUND TRUTH DATABASES AND OTHER STUDIES FOR REGIONAL SEISMIC RESEARCH

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ABSTRACT

In the second year of this project, the main objective continues to be the formation of databases providing ground truth for regional seismic research conforming to the latest Center for Monitoring Research (CMR) schema. The effort focuses on events in the CMR Calibration Event Bulletin (CEB) from China, the former Soviet Union, and North America. Selected CEB events are re-analyzed using the seismic analysis software *geotool* starting with the Reviewed Event Bulletin (REB) solutions. Modifications to the original REB results include mostly arrival phase re-timings and adding missed phases, including depth phases. New waveform data are retrieved and analyzed from available IRIS stations mostly within 25 degrees distance. A modified version of *LocSAT*, called *Locate*, which uses a graphical user interface and allows interactive processing to generate location results, is used to locate the CEB events. Two sets of location results per event are derived: the first by using only the revised IDC arrivals, and the second by using both the IRIS and revised IDC data.

Analysis of datasets of 70 CEB events in China and 80 CEB events in the former Soviet Union (FSU) has been completed. Re-analysis of the Chinese data included using waveforms from over 140 IDC stations contributing over 4000 arrivals, supplemented by nearly 3800 waveforms from over 130 IRIS stations providing nearly 2300 additional arrivals. Similarly, the FSU data included not only waveforms from about 130 IDC stations contributing over 4000 arrivals, but also nearly 4000 waveforms from more than 160 IRIS stations providing over 2300 new arrivals. The most important contribution of the IRIS data is the addition of a large number of arrivals from regional phases. Similar analysis of CEB events in North America, based on the use of both IDC and IRIS stations, is in progress.

An examination of the travel time residuals versus epicentral distance, based on the use of IASPEI91 travel time tables, for both the Chinese and FSU datasets indicated that the residuals for all phases, derived from the combined use of the IRIS and revised IDC data, show both positive and negative scatter which increases with distance. The residuals are small for P, Pn, and Pg, with average values less than 0.5 sec. But for both Sn and Lg, the residuals are large and mostly negative (average values several sec negative), suggesting that the IASPEI91 tables for these two phases are not strictly valid for these two regions.

Other studies included an examination of aftershock activity due to a 100 ton chemical explosion at the Degelen, Kazakh Test Site on 22 August 1998. Analysis of aftershock data from a suspected nuclear event is one of the principal technologies employed for the on-site inspection part of CTBT monitoring. All available aftershock data for 25 days after the explosion were first retrieved and scanned. Seismic events recorded by a local network of six three-component stations indicate at least 669 possible aftershocks that were recorded at two or more stations. The events show strong attenuation with distance and no clear evidence of diminished activity after 25 days. Locations of 14 well recorded aftershocks, obtained by using a closely spaced network of recording stations, showed all epicenters to lie within less than 200 m of the 100-ton shot. This implies that aftershock locations determined within several days of the detonation time of an explosion may provide a fairly accurate location of ground zero.

OBJECTIVE

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The overall objective of this project is to improve monitoring of the Comprehensive Test Ban Treaty (CTBT), which requires the ability to detect, locate and identify seismic events. Once a suspicious event has been detected, its location must be accurately determined as a precursor to event identification and potential on-site inspections. Following last year's effort (Henson *et al*., 1999), the main objective continues to be the formation of databases which provide improved ground truth for events in China, former Soviet Union (FSU), and North America, as selected from the Calibration Event Bulletin (CEB) established at the Center for Monitoring Research (CMR). Re-analysis of the International Data Center (IDC) data combined with retrieval and analysis of selected Incorporated Research Institutions for Seismology (IRIS) data leads to improved location and depth estimates of CEB events. Additional work included an examination of aftershock activity due to a 100 ton chemical explosion at the Degelen, Kazakh Test Site; this is useful because analysis of aftershock data from a suspected nuclear event is one of the principal technologies employed for the on-site inspection part of CTBT monitoring.

RESEARCH ACCOMPLISHED

(a) Formation of Databases and Related Study

Selected CEB events from China, the former Soviet Union, and North America are re-analyzed using the seismic analysis software *geotool*, starting with the Reviewed Event Bulletin (REB) solutions. The original REB results are improved by re-timing phase arrivals and adding missed phases, including depth phases. New waveform data from IRIS stations are retrieved and the arrival times of various phases are determined. Note that the IRIS stations are selectively retrieved so that mostly regional and near teleseismic distances are represented (up to 25 degrees), with additional data for teleseismic stations which fall within the largest azimuthal gap (up to about 50-70 degrees) and near the PKP caustic. The CEB events are re-located by using a modified version of *LocSAT*, called *Locate*, which uses a graphical user interface and allows interactive processing to generate location results. For each event, two sets of location results are derived: the first by using only the revised IDC arrivals, and the second by using both the IRIS and revised IDC data.

Analysis of datasets of 70 CEB events in China and 80 CEB events in FSU has been completed. Waveforms from over 140 IDC stations contributing over 4000 arrivals, supplemented by nearly 3800 waveforms from over 130 IRIS stations providing nearly 2300 additional arrivals, contributed to the re-analysis of the Chinese data (Henson *et al*., 1999). The FSU data included waveforms from about 130 IDC stations contributing over 4000 arrivals, and nearly 4000 waveforms from more than 160 IRIS stations providing over 2300 new arrivals. The REB epicentral locations of these 80 FSU events are shown in Figure 1 along with the locations of both IDC and IRIS stations that recorded these events. Note the large number of IRIS stations at regional distances for most of these events. A comparison of the propagation paths available in the original REB dataset and the IRIS and revised IDC dataset for Pn and Lg, shown in Figures 2 and 3, respectively, clearly demonstrates the significant contribution the IRIS data have made in providing additional regional phases.

The results obtained from analysis of all 80 CEB events in FSU were delivered to the CMR. Each event location consists of four CSS3.0 files, including the origin, origerr, arrival, and assoc database tables. Therefore, a total of 640 such database files were delivered to CMR ready for installation into their CEB database. All IRIS waveform data that contributed to the 80 CEB events in FSU were also delivered to the CMR on one 8 mm archive tape in CSS3.0 format. Analysis, similar to that carried out for the Chinese and FSU events, has been completed for about 100 CEB events in North America by using waveform data from both IDC and IRIS stations.

The *Locate* software uses the IASPEI91 tables in order to obtain predicted travel times for a suite of seismic phases at various distance and depth ranges. Frequently, the arrival time residuals for various phases were observed to be too large to be selected as defining phases. In order to determine whether these residuals show any systematic trends, we made plots of the dependence of observed arrival time residuals with distance for P and the four regional phases, Pn, Pg, Sn, and Lg for both the China and FSU data. The residuals for all phases, based on the "revised IDC + IRIS" arrival times, show generally larger scatter (both positive and negative) with increasing distance. The residuals are small for P, Pn, and Pg, with average values less than 0.5 sec. But for both Sn and Lg, the residuals are large and mostly negative (average values several sec negative), suggesting that the IASPEI91 travel time tables for

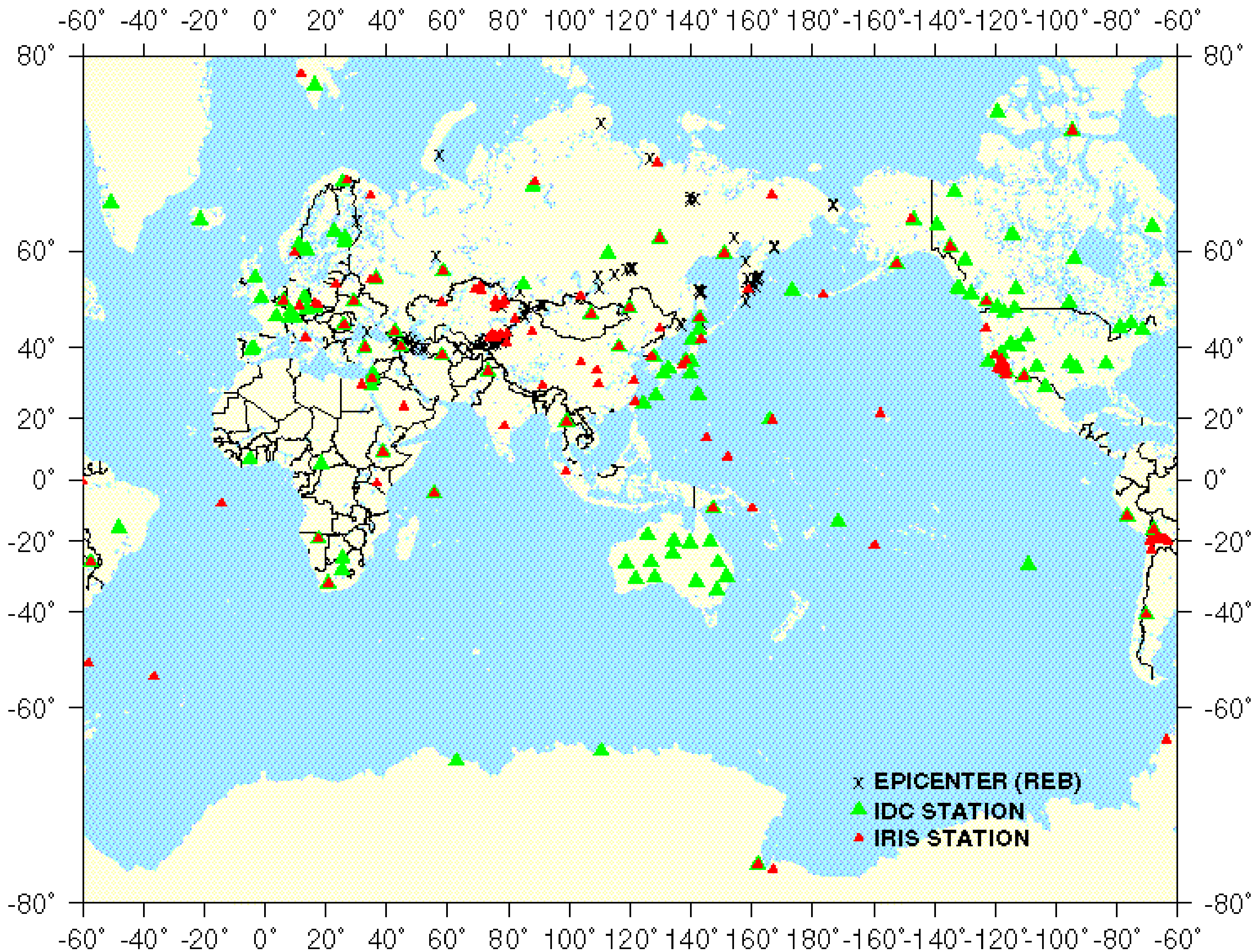

Figure 1. REB epicentral locations of 80 events in the former Soviet Union (FSU) and the IDC and IRIS recording stations which provided waveform data analyzed in this project. Note the large number of IRIS stations at regional distances for most of the 80 FSU events.

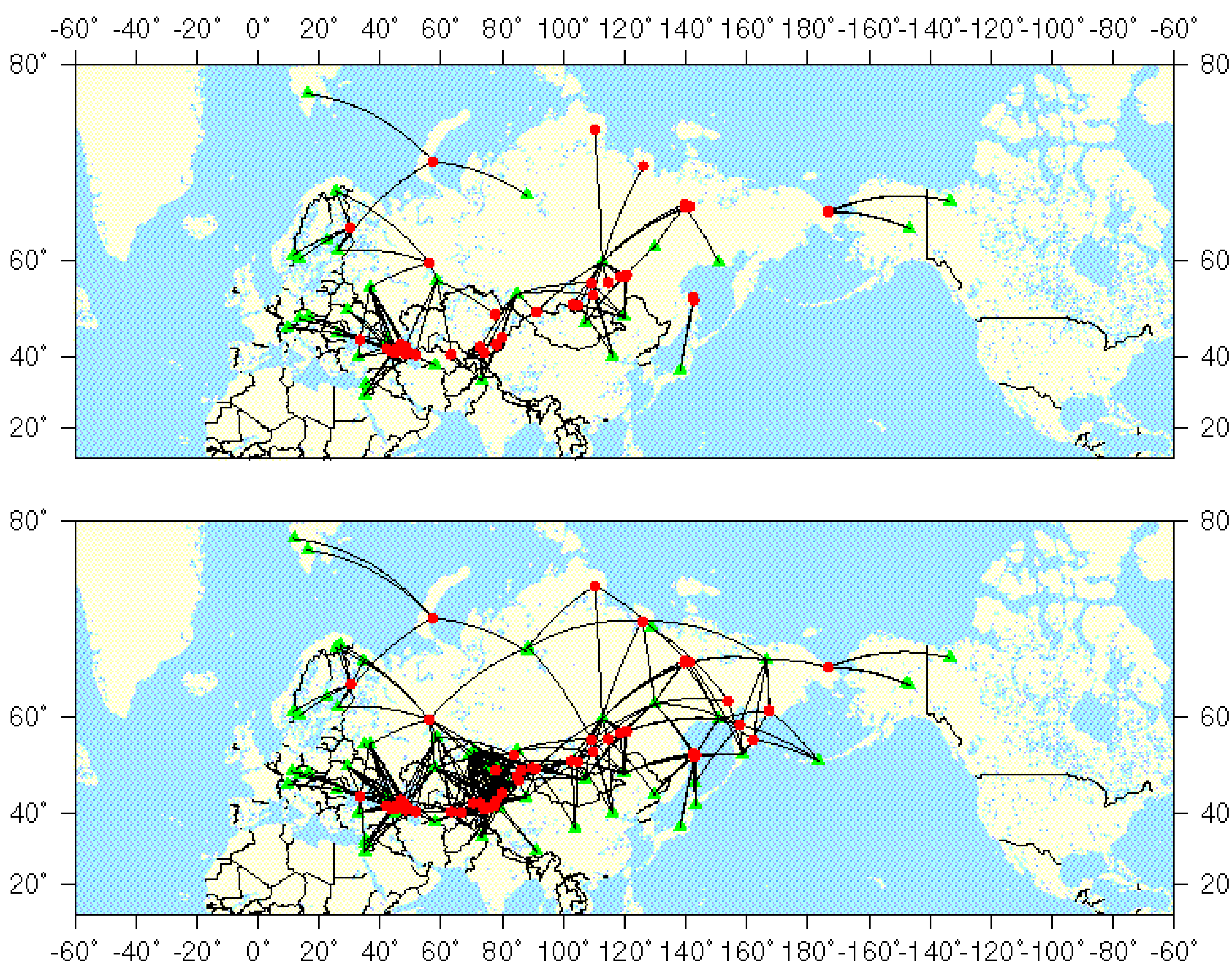

Figure 2. Comparison of Pn phases and corresponding propagation paths for the FSU available in (a) original REB dataset showing 45 events and 111 paths, and (b) IRIS and revised IDC dataset showing 65 events with 479 paths. The IRIS data provide a large number of additional Pn arrivals.

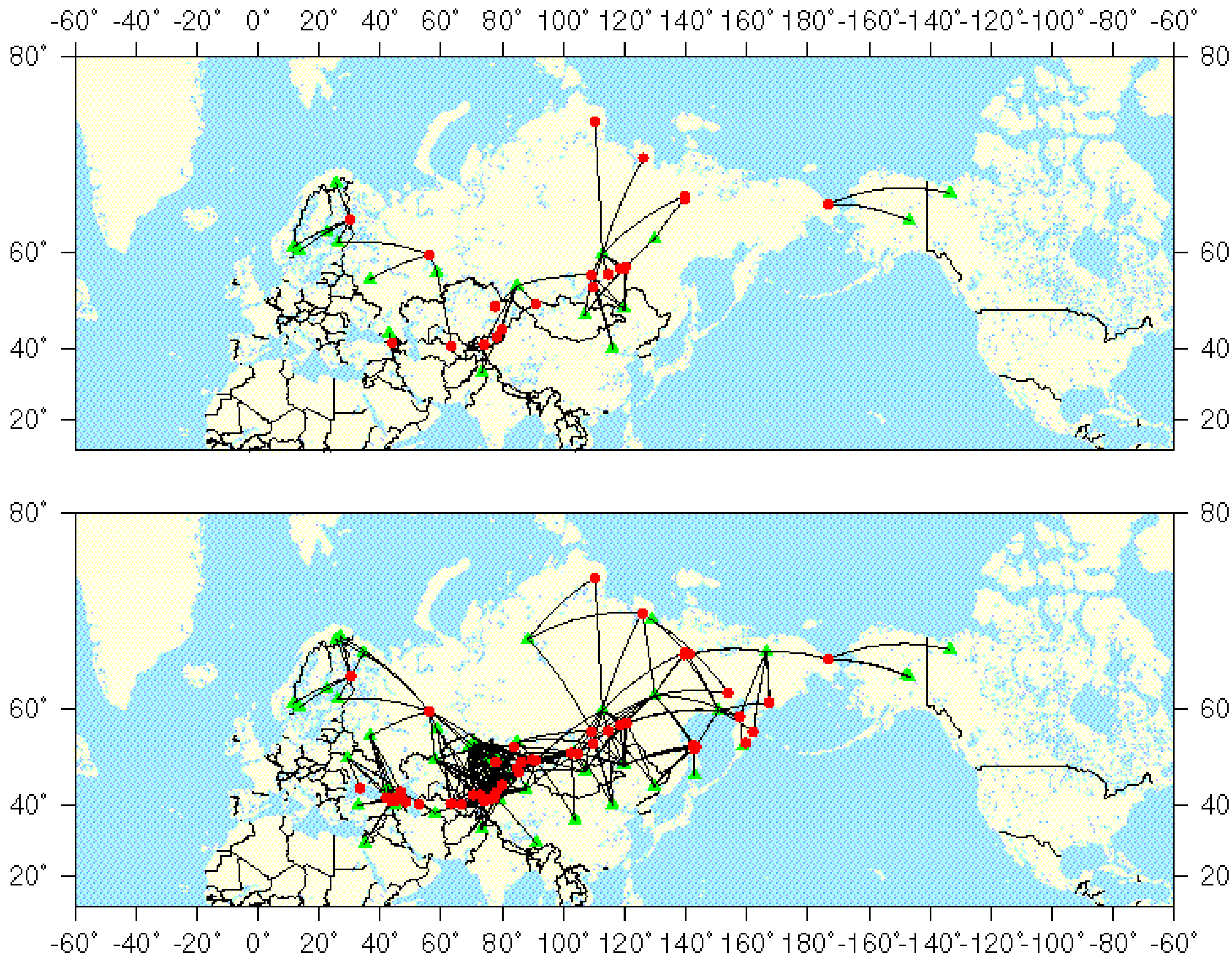

Figure 3. Comparison of Lg phases and corresponding propagation paths for the FSU available in (a) original REB dataset showing 21 events and 41 paths, and (b) IRIS and revised IDC dataset showing 63 events with 438 paths. The IRIS data provide a large number of additional Lg arrivals.

Sn and Lg are probably not applicable to either of the two regions. Figure 4 shows the results for Pn and Sn for epicentral distances up to 15 degrees. All data points are shown along with the moving medians (each with a window length of 2 degrees and shift of 0.5 degrees). For distances up to about 10 degrees, a comparison of the residuals for China and FSU shows significant differences. The residual medians for China and FSU differ by about 0.7 and 2.8 sec for Pn and Sn, respectively, indicating that both Pn and Sn arrive relatively later for events in China than those in FSU. A possible reason is generally deeper Moho for most seismic events in China as compared to those in the FSU, as indicated by the global crustal model of Mooney *et al*. (1998; see Plate 1d, p. 733).

(b) Analysis of Aftershock Data from a 100-ton Calibration Shot

Under the CTBT, the initial detection capability for a treaty violation will come from the International Monitoring System (IMS). However, in some cases, the IMS may not be able to provide conclusive evidence and an on-site inspection (OSI) may be used to gather evidence to determine the nature of the event. Aftershock monitoring can be used to accomplish two main goals: (1) to reduce the OSI search radius by locating the aftershocks, and (2) to help determine the source type of the event (*e.g*. explosion or earthquake). Several early studies (*e.g*. Hamilton and Healy, 1969; Ryall and Savage, 1969) indicated that explosions can stimulate significant seismic activity and that post-shot seismicity is constrained to the vicinity of the explosion in both space and time. Numerous studies *(e.g*., Jarpe *et al*., 1994; Sweeney *et al*., 1996; Gross, 1996) noted differences in the spectral characteristics of aftershocks from various natural and man-made seismic sources, including the Non-Proliferation Experiment of 22 September 1993, consisting of about 1 kt of chemical explosives.

We investigated the characteristics of seismic events following a 100-ton chemical explosion detonated at the FSU's nuclear test site at Degelen, eastern Kazakhstan on 22 August 1998 and examined their usefulness for on-site inspection. This explosion was carried out as a calibration experiment for the CTBT verification as a part of the closing of nuclear test tunnels under the Nunn-Lugar Cooperative Threat Reduction Program (Leith and Kluchko, 1998). The engineering and geological characteristics of the tunnel in which this experiment was carried out have been described by Leith *et al*. (1997). A topographic map of the Degelen Mountain region can be seen in Figure 1 of Gupta and Wagner (1992) and Figure 2 of Leith *et al*. (1997).

Analysis of high-frequency seismic data from a local network of six three-component stations monitoring the chemical explosion at the Degelen test site was started by first retrieving and scanning all available waveform data covering a period of 25 days. One of the stations was at ground zero, whereas the other five were within a distance of about 2.5 km. As many as 669 possible aftershocks were observed between 22 August to 15 September 1998 at two or more stations during 25 days of monitoring. Figure 5 shows a histogram displaying the distribution of 669 events, starting at the detonation time (05:00 hrs) of the calibration shot. No data were available for the first four hours. The distribution of events is uneven, with a significant increase in the number of seismic events after 16 days. This large increase in the number of seismic events after Day 16 is unexpected and appears to be in conflict with earlier studies of aftershocks from chemical and nuclear explosions which show seismic activity generally decaying with time (Jarpe *et al*., 1994; Smith, 1997). A possible reason could be delayed collapse of a portion of the tunnel weakened by the explosion, especially because the tunnel is located in a region of complex geology, including faults and fracture zones (Leith *et al*., 1997). Several man-made activities, such as removal of collapsed debris (mucking) and installation of ventilation and electrical systems, are known to occur at this site; these provide other possible explanations. An examination of amplitude data from various stations also indicated that the amplitudes of aftershock recordings attenuate strongly with distance and there was no evidence of reduced activity after 25 days.

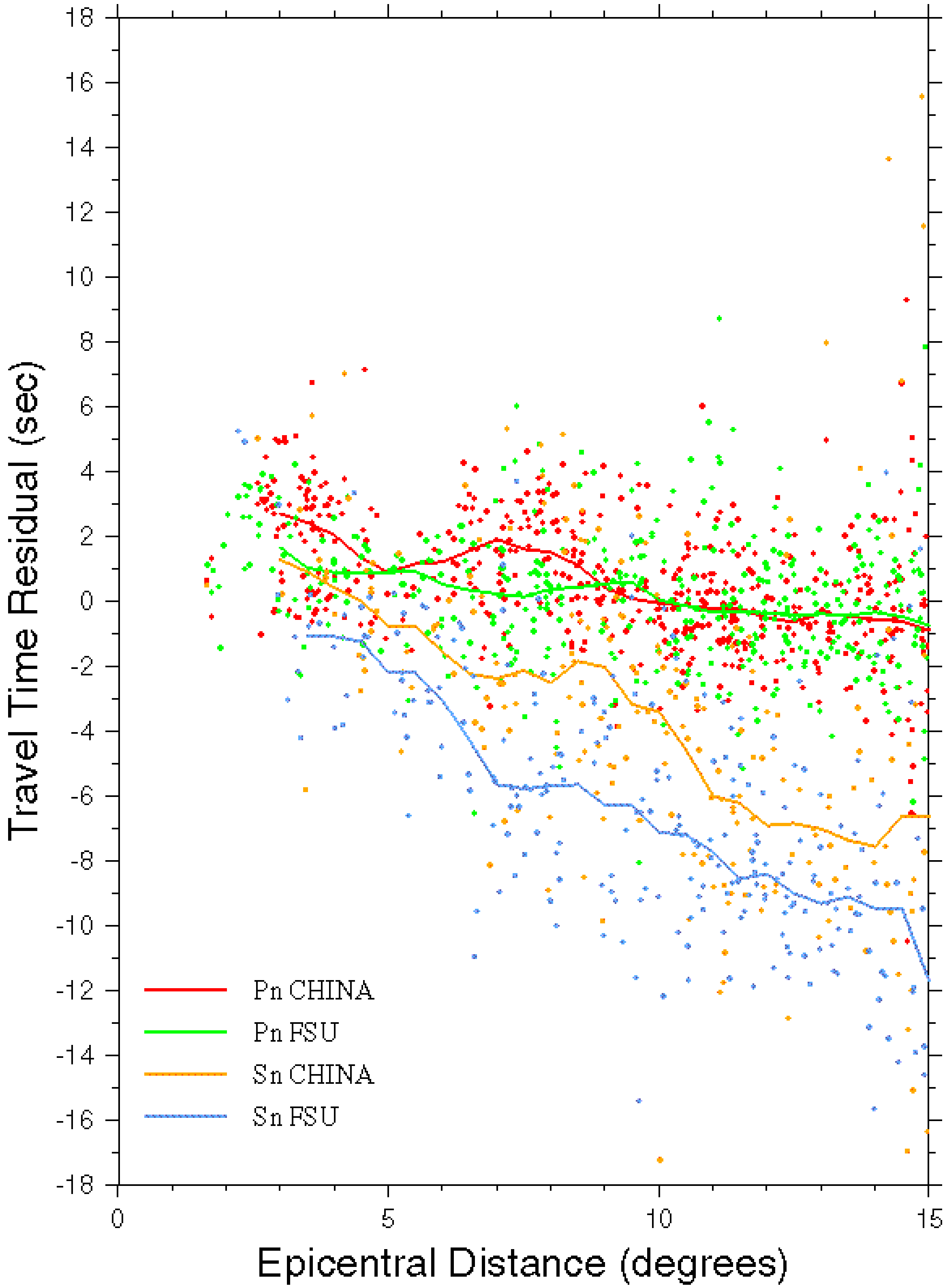

Figure 4. Travel time residuals for Pn and Sn for China and FSU showing data points and moving medians. For distances up to 10 degrees, the residuals indicate that both Pn and Sn arrive relatively later for events in China than those in FSU; a possible reason is a relatively deeper Moho under

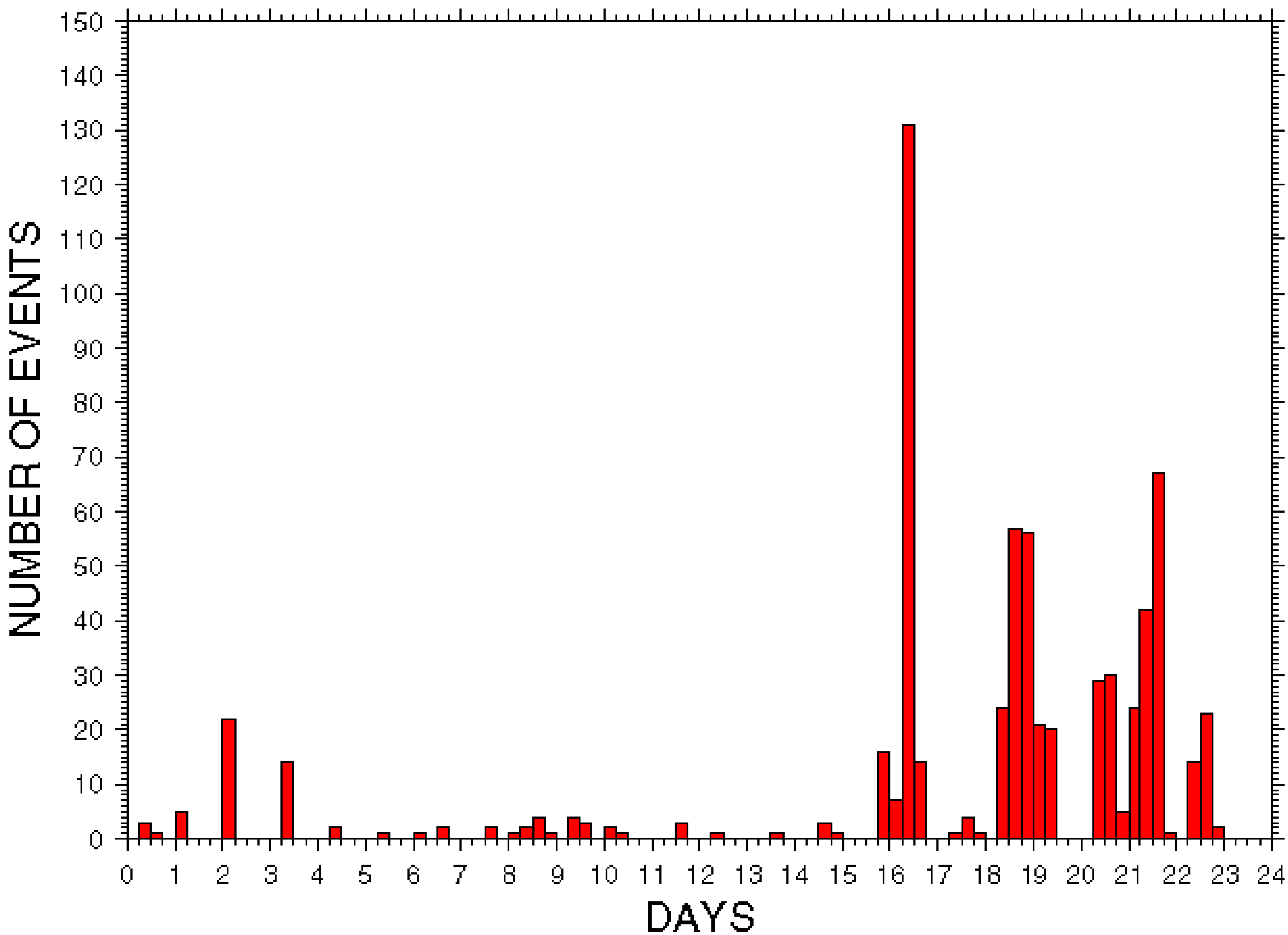

Figure 5. Histogram showing the distribution of 669 aftershocks between 22 August and 15 September 1998 (25 days), starting at the detonation time of the calibration shot. No data were available for the first four hours. The distribution of events is uneven and a significant increase in the number of seismic events is observed after 16 days, perhaps due to tunnel collapse or some man-made activity.

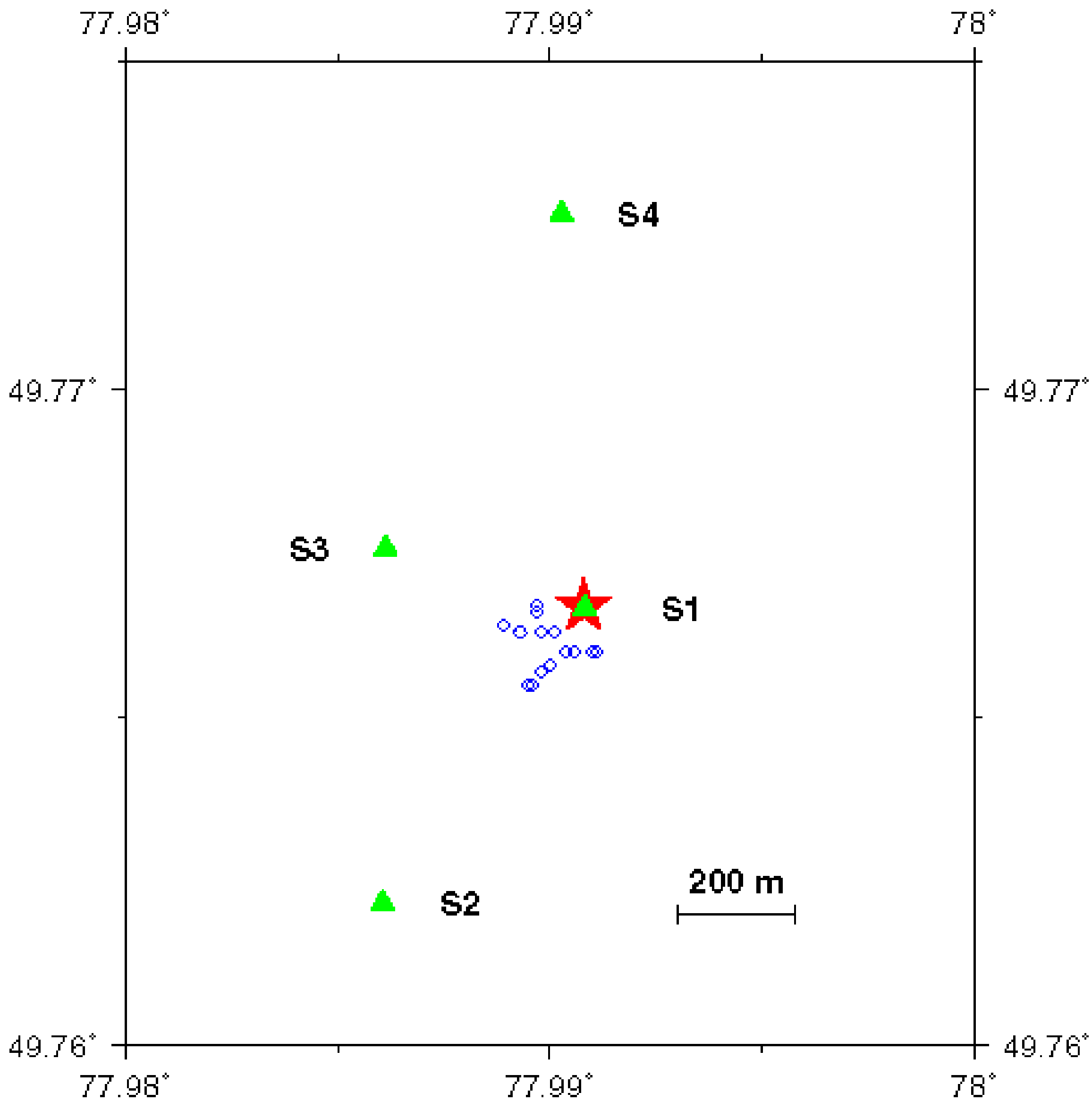

Figure 6. Epicentral locations of 14 aftershocks of the 22 August 1998 Degelen shot. Station S1 is at ground zero, whereas the other five stations lie within a distance of about 2.5 km (only four stations are shown here). All epicenters plot within less than 200 m of the main event, suggesting that aftershock locations may provide a fairly accurate location of the main shot.

Fourteen (14) aftershocks were found to be well recorded at four or more stations. Their epicentral locations, based on P-wave arrivals, showed all epicenters to lie within less than 200 m of ground zero of the 100-ton shot (Figure 6). These aftershocks, distributed over a period of about 20 days, suggest that aftershock locations determined within several days of the detonation time, may provide a fairly accurate epicentral location of the explosion. It seems therefore that monitoring of aftershock activity, even if initiated several days after an explosion, can be useful for on-site inspection of a region in which a suspicious event has occurred.

CONCLUSIONS AND RECOMMENDATIONS

Formation of databases with significantly improved ground truth can be accomplished by a combination of re-analysis of the IDC data and retrieval and examination of data from other available sources such as the IRIS. Similar to the Chinese dataset, the most important contribution of the IRIS data to the FSU dataset is the addition of a large number of arrivals from regional phases, so that solutions based on the combined use of both IRIS and IDC data provide improved estimates of both epicentral location and depth in comparison to the original REB solution. Such analysis should also be carried out for other regions of the world. Analysis of aftershock data from a 100 ton chemical explosion at the Degelen, Kazakh Test Site demonstrates that monitoring of aftershock activity from a suspected nuclear event within several days of its detonation may provide a fairly accurate location of ground zero. It will be useful to carry out similar studies of possible aftershocks from large explosions at other test sites.

Key Words: Database, ground truth, explosion aftershocks, CTBT, regional seismic research

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